

A Comprehensive Review of Existing Urban Energy Models in the Built Environment

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Abstract This review considers previous researches that dealt with energy modelling in the built environment at different urban spatial scales. Up to now, modelling approaches focus on energy flow simulation in urban area from generation to distribution and finally consumption. Dependent on the energy flow direction and focus of these models in urban energy system, they are categorized in three distinct groups: supply, demand and integrated models. A critical evaluation of each category of these models based on the same criteria is provided. As a result, some of the main aspects that are missing in the existing models are highlighted, including: integrated multilayer models, spatial implications of renewable energy technologies and integration of simulation and optimization methods.

1 Introduction

Cities as a main consumer of energy resources need to transform from fossil fuel based energy systems to renewable energy systems to fulfill the renewable energy ambitions. The built environment with almost 40 % of the total energy demand has

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a substantial contribution in this transformation process. The energy characteristics of building sector are diffuse and complex. Therefore, comprehensive models are needed to capture the different aspects of them to support urban planners in developing integral city transformation plans. Before city councils commit to significant new energy policy initiatives, they require insight into the possible consequences of them and improve their understanding of the energy flow in urban areas. Different models aim to describe these processes and attempt to predict how it might be changed over time (Keirstead et al. 2009).

Advances to date have been based on predicting the energy demand of groups of buildings, mostly based on their functions—residential, commercial or industrial—as distinct categories. These models estimate the energy demand of stocks of buildings based on extrapolation of results from representative building typologies. A similar approach was developed for modeling demand in domestic building stock based on combinations of building type and household composition (Shimoda et al. 2004). On the supply side, modeling availability of renewable energies, particularly, solar and wind in urban area has a reasonably long history, dating back to simple computer simulation models to assist site layout planning (Robinson et al. 2007a, 2008). More recently, supply models have focused on evaluation of renewable energy potentials with geographical information system (GIS) technologies and remote sensing data. Lately, researchers tend to develop integrated models. Integrated models such as; SEP, LT-Urban, SUNtool, CitySim and SINCITY focus on the whole urban energy system. The typical goal of these models is developing design tools for planners to support evaluation of alternative scenarios.

This review provides an up to date overview of the modeling approaches that are developed to simulate the energy flow in urban built environment. A vast variety of modeling techniques are used to simulate energy production, distribution and consumption. These models have different characteristics, strengths, weaknesses, capability and applicability. They are usually constructed based on the different assumptions, input data and level of details (Swan and Ugursal 2009). Accordingly classification of them can be done in different ways. Based on the spatial and temporal dimensions, cities are composed of several spatial levels, such as building, neighborhood, district or city that in each level specific factors influence the energy flow. Therefore, the categorization of energy models can be done based on these spatial scales (Owens 1986). The most common way of categorization of urban built environment energy models is based on the application focus of these models in the urban energy system. Supply and demand models are most frequently used. Recently, researchers are interested in developing integrated models that include supply and demand models. Each of these models relies on different levels of input data, calculation techniques and different applicability. A critical review of each of these models is provided based on the specific criteria including: spatial features (scale and dimension), temporal resolution, simulation approach and analytical method. In this review, in Sects. 2, 3, 4 we discuss the supply, demand and integrated models subsequently. Then we discuss aspects that are missing in current urban energy models. We finish with some conclusions.

2 Supply Models

The first category of energy simulation models in the urban built environment is related to the supply side of urban energy system. The typical goal of these models is estimating the potential availability of different kinds of renewable energy resources in urban fabrics at different spatial scales. This type of models has a quite long history and come back to the simple computational and mathematical techniques to aid planners in large scale urban layout planning (Robinson et al. 2008). In recent years the main focus of urban designers and planners in sustainable design of urban environment have been based on the concepts such as bioclimatic and smart design, building orientation and daylight access that are more dealing with the efficient use of solar energy either in terms of solar active or passive design strategies. In this regard modeling availability of solar radiation in urban fabrics for use by converting technologies or natural lighting has gained much attention. Accordingly in this part, the main focus of supply models will be on solar energy simulation models.

Mardaljevic and Rylatt (2003) proposes an approach for evaluating the total annual irradiation incident on building facades in urban settings based on a physical-based rendering approach and data-visualization techniques to generate maps of annual irradiation. The sun and sky irradiation maps are evaluated and the sky contribution is calculated using realistic, non-isotropic models for the sky radiance distribution. Compagnon (2004) used a similar approach, but based on pre-processing the sky radiance distribution rather than post-processing results for individual skies/suns. Moreover, they proposed a methodology to quantify the potential of facades and roofs located in urban areas for active and passive solar heating and photovoltaic electricity production in London. Solar irradiation and illuminance values obtained through numerical simulations form the core part of the method. In an integrated approach with GIS, Gadsden et al. (2003) developed a general methodology of solar energy planning for energy advisers that determines the potential for generating solar energy. The methodology identifies suitable dwellings for installing solar panels and quantifies the potential energy savings and reductions.

In a European project, Sustainable Urban Neighborhood Tool (SUNTool) was developed using a slightly more computationally accurate way of simulating irradiation with a cumulative sky. The researchers proposed a technique, which produces annual irradiation images using the popular ray-tracing tool RADIANCE. This involves the use of a pre-processor, which generates a cumulative sky radiance distribution that the ray-tracing program can reference to at run time (Robinson and Stone 2004). The cumulative sky may be described in terms of either a global radiance distribution for a discretized sky vault or a diffuse discretized radiance distribution with either hourly or a statistical subset of suns.

Recently new data extraction and acquisition technologies from aerial images such as Remote Sensing and Light Detection and Ranging have been used in urban planning domain. Agugiaro et al. (2011) use these technologies for estimating solar radiation on building roofs in a complex landscape area. The approach was

Table 1 Characteristics of reviewed supply models

Features Models	Years	Spatial scale	Spatial analysis	Temporal dimension	Renewable energy sources	Analysis method
Mardaljevic	2003	City	3D	Annual	Solar radiation and natural light	Simulation
Gadsden	2003	City	2D	Annual	Solar thermal energy and electricity	Simulation
Compagonen	2004	Neighborhood	3D	Monthly	Solar radiation and day light	Simulation
Robinson	2004	Neighborhood	3D	Hourly	Solar radiation, Water, Waste	Optimization
Agugiario	2011	Regional	3D	Daily	Multi scale solar radiation	Estimation
Carlson	2011	City	2D	Monthly	Solar reflectivity	Simulation
Vettorato	2011	Regional	2D	Annual	Solar radiation, biomass, geothermal	Simulation, Optimization
Strzalka	2012	District	2D	Monthly	Solar electricity energy	Optimization

based on a multi-scale solar radiation estimation methodology that combines 3D data, ranging from regional scale to the architectural scale. Moreover, they present a very high-resolution geometric model of the building roofs by advanced automated image matching methods. Models are combined with raster and vector data sources to estimate the incoming solar radiation hitting the roofs (Agugiario et al. 2012). Based on the POLYCITY project, Strzalka et al. (2012) develop a four-step methodology that uses Laser Scanning data along with Geo-Media for finding the potentials of rooftops for the PV-system. These steps include; collect the laser scanner data, introduction of a GIS software tool as an interface to visualize data, estimate the suitable roof areas and calculate the solar roof potential for producing the electrical energy from the PV-systems. Estimating the potential of urban scale implementation of reflective roof materials in built environments for estimating the potential energy saving is another research field, which is considered in recent years. Jo et al. (2010) develop a methodology for assessing the potential capacity of installing reflective roofs in an urbanized area. In this methodology, remote sensing image data combined with a building energy models to quantify the rooftop reflectivity and predict the potential electricity savings. Based on matching energy supply and demand in urban areas, Vettorato et al. (2011) developed a three-step framework to compare the potential supply of renewable energy technologies and the energy demand of buildings at local scales.

Table 1 shows the main characteristics of the reviewed supply models.

3 Demand Models

Around 40 % of the total energy demand in urban area is consumed in the built environment (Sunikka 2006). Hence fulfilling any energy ambitions requires a considerable transformation of the current pattern of energy use in this sector. In general energy demand models focusses on the evaluation and estimation of energy consumption in built environment. Building energy characteristics are very broad and complex issue and in simulation and estimation need to consider a wide range of aspects such as physical, constructional and behavioral characteristics in different spatial and temporal levels. This review based on the econometric and engineering approaches attempts to highlight more physical and constructional aspects of urban built environment. Behavioral considerations and policy implications associated with it are beyond the scope of this study. To date, researchers use two fundamental different classes of modeling techniques for estimating energy use in the built environment; the top-down and bottom-up techniques (Bohringer et al. 2007). Recently spatial evaluation of the energy demand has been added incorporating new data collection techniques. In the next subsections, each of these approaches is elaborated in more detail.

3.1 Top-Down Approach

The top-down modeling approach works at the aggregated and macro level, and treat the built environment as energy sink (Swan and Ugursal 2009). These models tend to be used to investigate the interrelationships between the energy sector in urban area and other aspects such as economy and socio-demographic characteristics of the large scale (Kavgic et al. 2010). A variety of variables can be used in these models, such as socioeconomic variables, climatic conditions, stock building construction rates etc.

These models are categorized into two main subgroups, econometric and technological models. Econometric models as evident from their names are based on interconnection between energy use with socioeconomic variables to examine the connection between the energy sector and economic output. Technological models examine the energy consumption to more detailed technological and physical characteristics of the built environment that influence energy use, such as: saturation effects, technological progress, and structural change (Johnston 2003). The use of these approaches come back to the energy crises of the late 1970s, when researchers try to investigate the impacts of the energy price and changing in consumption patterns on the end user behaviors in high spatial levels (Swan and Ugursal 2009). The first types of these models were more econometric models based on statistical data that energy consumption expressed as a function of simple econometric variables. Hirst (1978) proposed a U.S. residential annual energy consumption model that is based on the economic and housing ownership changes,

and the model has developed into an economic model including housing ownership and technical parameters. His work was developed over the following years and resulted in an econometric model, which had both housing and technology components (ONeal and Hirst 1980). Saha and Stephenson (1980) developed an engineering-economic model to simulate residential energy use in New Zealand that is sensitive to major technological, economic and demographic determinants. Based on Genetic Algorithm (GA) the Energy Input Estimation Model was developed by Ozturk et al. (2004) that used to estimate Turkey's future residential-commercial energy input demand based on GDP, population, import, export, house production, cement production and basic house appliances consumption figures. This model estimates the future projections on energy consumptions and examines the effect of the design parameters on the energy input of the sector. To support the decision-making process by benchmarking of the environmental performance of buildings between real-estate managers and municipal administrations, Tornberg and Thuvander (2005) present a GIS implemented energy model for the building stock in the city of Goteborg. Energy data comprises energy source and amount of energy used for heating, hot water, and electrical appliances.

3.2 Bottom-Up Approach

The bottom-up models are built up based on the data on an individual level to investigate the contribution of end user on energy usage in urban and regional level. These models can be used for simulation of energy use for individual occupants, building or groups of buildings and then extrapolate results to represent the city or region, based on the representative weight of the modeled samples (Yamaguchi et al. 2007). As the bottom-up models work on a micro level, thus for evaluating the energy use, they need extensive databases of empirical data to support the description of each user (Shorrocks and Dunster 1997). Advances to date in the use of this modeling approach have been based on evaluating the energy consumptions of groups of buildings (residential, commercial or industrial buildings) as distinct categories. Michalk et al. (1997) developed a structural model for energy use in the residential sector whose customers were segmented into four main categories. The model provides energy-use patterns for each category of customers for selected customer samples. Lariviere and Lafrance (1999) present a statistical model that establishes a relationship between the annual electricity consumption per capita and some variables which characterize a sample of Canadian cities, include, urban density, demography and meteorological data. In the UK Jones et al. (1998, 2007) develop a model to estimate the energy demands and associated emissions for a municipality's stock of buildings based on the extrapolation of results from 100 representative building typologies for the case study site of Neath and Port Talbot. Using a same approach, Shimoda et al. (2004) proposed an energy demand model for Osaka city based on the occupants' schedule of living activities, weather data and energy efficiencies of appliances and

dwellings. By summing up the simulation results for various household categories, total energy consumption in the residential sector estimated. A significant difference in this model is incorporating occupational characteristics such as occupants' presence and use of appliances in the modeling using detailed survey statistics. Yamaguchi et al. (2003) develop a bottom-up approach based on the constructional features and occupancy characteristics. It provides insights into the changes required in all the components of urban energy systems from the equipment level to the entire building and systems level. Moreover, Yamaguchi et al. (2007) increased their scale of analysis to the city scale and proposed a general methodology based on the prototypical approach. In this methodology, in general building stock is divided into several categories based on the physical or behavioral characteristics and then energy use for each category is quantified using prototypical buildings that representing a whole building stock category. The model revealed how the classification of building stock according to a number of building properties improves the accuracy of the simulation model. To optimize the generation and distribution of energy in district heating/cooling systems and to predict accurate energy demand profiles, Kim et al. (2009) developed a detailed building simulation technique based on the location, orientation and configuration variables that was employed for the prediction of individual building energy load patterns. The model shows that the effect of model resolution is more evident in the winter, the effect of building orientation is clearer in summer, and the effect of shade from adjacent buildings is greater in winter.

3.3 Spatial Evaluation of Energy Demand

The energy demand of building sector can be evaluated quickly and robustly without costly on-site measurements (Rylatt et al. 2003). This part reviews integration of urban energy demand models with new technologies in data extraction and management in urban planning domain i.e. Geographical Information Systems (GIS) and Remote Sensing. It demonstrates how these technologies can be employed to facilitate the acquisition and extraction of building data and spatial parameters from the plan form of buildings. These tools fulfill the large data requirements of urban models without the need of visual inspection and long survey of the properties (Jones et al. 2007). Rylatt et al. (2003) introduced a prototype general domestic energy modeling approach to the estimation of so-called baseline energy consumption. It shows how useful data relating to the plan form of dwellings such as the plan form and its area, the size of the perimeter, the exposed perimeter size, the built form type and the orientation can be derived from digital maps to use in energy analysis. Heiple and Sailor (2008) combine annual building energy simulations for city-specific prototypical buildings and available Geospatial data in a GIS framework for estimating hourly energy consumption profiles in the building sector at spatial scales down to the individual parcel. Based on a systematic approach, Mavrogianni et al. (2009) combines GIS databases and a

modified version of the Standard Assessment Procedure algorithm to estimate the space heating demand of urban domestic energy users for exploring the impact of urban built form on the levels of domestic energy consumption in London. Comparison of the model outputs with top down energy statistics for annual household energy consumption indicates that the model ranks areas based on their domestic energy demand with relative success. Recently most researchers tend to use sophisticated spatial models in their simulations i.e. 3D modeling. Beginning in the early 1990s, first 3D city models were built to have a 3D representation of a city (Lippold 2010). Until today, the establishment of a comprehensive 3D model is still the focus of many researchers around the world. Nowadays by employing high quality remote sensing data, technology capability has reached a level where 3D analysis can be achieved much easier. Beside that cloud computing infrastructures and software applications technology provides a solid and improvable base for 3D and sophisticated analysis (Robinson et al. 2007a, 2008). As a result, 3D city models can be applied as a promising tool for energy evaluation on large-scale areas. Strzalka et al. (2010) develop an urban energy management tool to evaluate the heating demand of urban district and analysis appropriate measures to improve the building energy performance. For this purpose, a method was developed that enables an automatic extraction of the building's heating volume from a Geo-information system. LAIDR technology was used to extract the buildings volume, building footprints and the measured building heights and finally allows generating a 3D city model of the analyzed area. Based on this 3D model required data for analysis in terms of input file is generated. Table 2 shows the main characteristics of the reviewed demand models.

4 Integrated Modeling Approach

Modeling of urban energy system into separate parts will not cover all aspects of the issue; therefore, modelers tend to develop a more holistic model of this system. In urban scale, due to the complex structure of urban systems and plurality of constituent elements, simulation of system and their subsystems are involved with a variety of complicated and interrelated features. As a result, for comprehensive modeling in urban level even on a small scale, a large number of aspects such as spatial, functional, socioeconomic and technological variables should be taken into account. Hence the number of permutations is overwhelmingly large and the probability of identifying an optimal combination of these variables, increasingly reduced (Robinson et al. 2007a).

To date, the use of integral scenarios and models in evaluating urban energy performance are in the initial stages of development. Recently, some preliminary energy-economy optimization models-encoded with a set of structured, self-consistent assumptions and decision rules-have emerged as a key tool for analysis of energy at the national and international scales. For investigating the interrelationships between buildings, transport and industry in urban area based on the

Table 2 Characteristics of reviewed demand models

Features Models	Years	Spatial scale	Spatial analysis	Temporal dimension	Variables	Approach	Analysis method
Hirst	1978	National	-	Annual	Socioeconomic, Technical	Econometric	Estimation
O'Neal	1980	National	-	Annual	Socioeconomic, Technical	Econometric	Estimation
Saha	1980	National	-	Annual	Socioeconomic	Engineering, Econometric	Estimation
Ozturk	2004	National	-	Annual	Socioeconomic, Design	Genetic algorithm	Simulation, Optimization
Tornberg	2005	City	2D	Monthly	Socioeconomic, Physical	Engineering	Estimation
Michalk	1997	Regional	-	Monthly	Physical, Occupational	Engineering	Estimation
Lariviere	1999	City	-	Monthly	Physical	Engineering	Simulation
Shimoda	2004	City	-	Daily	Physical, Occupational	Prototypical approach	Simulation
Jones	2007	Municipality	2D	Monthly	Physical	Prototypical approach	Simulation
Yamaguchi	2007	District	-	Daily	Physical, Occupational	Prototypical approach	Simulation
Kim	2009	Building	-	Hourly	Physical	Building simulation	Optimization
Rylatta	2003	Neighborhood	3D	Weekly	Physical	Image processing	Optimization
Heiple	2008	Building	3D	Hourly	Physical	Prototypical approach	Optimization
Mavrogiani	2009	District	3D	Monthly	Physical	Prototypical approach	Simulation
Strzalka	2010	District	3D	Hourly	Physical	Image processing	Simulation

energy supply and demand, Jones et al. (1998, 2007) develop Energy and Environmental Prediction (EEP) model. EEP is a kind of environmental auditing and decision-making tool, which is based on GIS techniques and unified urban sub-models—housing, non-domestic, industry and traffic—to establish energy use by these sectors. Solar Energy Planning (SEP) was proposed by Gadsden et al. (2003) to establish the baseline energy consumption of domestic properties. It determines the possible potential for reducing demand using the three key solar technologies; passive solar design, solar heating panels and photovoltaic panel systems. As in these models, the analysis performed based on the 2D maps, the spatial variables in analysis were partially superficial. As part of European Union funded project, Ratti et al. (2000) develop LT-Urban model as a tool to support urban-scale building energy modeling by interfacing a simplified building energy model with image processing techniques to improve the scale of evaluations. By employing techniques from image processing and the Geo-sciences, an algorithm has been developed to derive the necessary urban form variables such as built up area, facade orientation and obstruction angle of the sky from digital elevation models. Although in this model 3D spatial model were used to assess the impacts of urban form on the acquisition of solar energy, but diversity of variables for identifying an optimal configuration of urban layout was very limited. Brownsword et al. (2005) based on linear programming develop an urban energy optimization model using energy supply data for solar photovoltaic and postal code information that simulates spatial and daily variations in energy demand. A linear programming optimization module was used to identify the most cost-effective measures to achieve specified energy reduction targets.

In a collaborative effort and in terms of a European project, SUNtool was developed as a decision support system for designers to optimize the environmental sustainability of master planning proposals (Robinson et al. 2007b). It was based on the integrated resource flow modeling of buildings of disparate uses. For considering of all energy aspects in neighborhood level, four sub models; radiation exchange modeling, reduced thermal modeling, stochastic modeling of occupant presence and urban plant modeling was embodied in it. Later, CitySim was developed to provide more sophisticated simulation of resource flows at neighborhood levels (Kampf and Robinson 2008). Its aim was support designers to optimize the performance of new and existing urban developments based on more spatial parameters. In this model, as the spatial variables of an urban development is infinitely large, a microsimulation model of energy flow are coupled with an evolutionary algorithm to identify a subset of urban design variables that have been parameterized. Such method was robust, but spatial scale of the model was still limited. In a more technical model, Girardin et al. (2010) developed EnerGIS as a GIS based urban energy model that simulate with sufficient detail the energy service requirements of a given geographical area to allow the evaluation of the integration of advanced integrated energy conversion systems.

Various studies have shown that energy flow in urban area is associated with city structure and urban form. However, this connection makes a paradox between demand and supply sides. On one hand, densification of cities reduces transportation

and buildings consumptions whereas on the other hand, densification has a negative impact on urban microclimate and renewable energy potential. Based on this assumption, Bonhomme et al. (2011) develop MORPHOLOGIC model that is a GIS platform, which calculates solar potential using a simplified model of shadows and evaluates the energy consumption of city blocks and allow urban planners to evaluate the best urban form to reduce GHG emissions. Energy is essential to the delivery of urban services. Integrating the urban layout models with the socioeconomic structure of the city to evaluate energy performance is a new challenge in integrated models that has a great potential for future researches. As an initial effort, SynCity was developed for integrating these two urban modeling approaches. In this model different aspects of urban energy system including; the layout of a city, the socioeconomic structure of it, activities, energy carriers and technologies are integrated. This synthetic toolkit, facilitate the integrated modeling of urban energy systems across all of the issues that related to the energy supply and demand in the city (Keirstead et al. 2009). Table 3 shows the list of these models along with the main criteria that used for evaluation of them.

5 Discussion of the Reviewed Models

From this review, it is evident that already there is a wide range of urban energy models. They are quite diverse in terms of spatial and temporal scales, energy side focus, analysis variables and methodological approaches that used for simulation. This review, without going too much into detail provides an overview of these models. By disaggregating, the energy models based on the energy flow direction and in terms of their main distinctive features, a consistent framework was provided for examining the different energy models. In this section their applications and development status is discussed.

5.1 *Supply and Demand Models*

The initial supply models were simple models for evaluation of solar passive strategies in urban built environments. But gradually, and with the emergence of other new renewable energy technologies, these models became sophisticated. Recently, a new computational technique is used, which produces daily/monthly/annual irradiation images using ray-tracing tools such as RADIANCE. In addition, by employing technologies such as Remote Sensing (RS) and Light Detection and Ranging (LIDAR), urban modelers could utilize a huge data extraction and management in evaluation of the availability of renewable energy resources in complex urban forms and morphologies. However, the sophisticated supply models, particularly based on the three-dimensional spatial models, are still in its early stages.

Table 3 Integrated models

Features Models	Years	Supply	Distribution	Demand	Spatial scale	Spatial analysis	Temporal dimension	Analysis method
LT urban	2000	+	-	+	Neighborhood	3D	Daily	Optimization
SEP	2003	+	-	+	City	2D	Monthly	Simulation
Brownsworld	2005	+	-	+	City	-	Daily	Optimization
EEP	2007	+	-	+	City	2D	Monthly	Simulation
SUNtool	2007	+	+	+	Neighborhood	3D	Daily	Optimization
CitySIM	2008	+	+	+	Neighborhood	3D	Daily	Optimization
SYNCity	2009	+	+	+	City	2D	Daily	Optimization
EnerGIS	2010	+	+	+	District	2D	Daily	Simulation
MORPHOLOGIC	2011	+	-	+	Neighborhood	3D	Monthly	Optimization

Each of the top-down and bottom-up energy demand models has their own strengths and weaknesses. Top-down approaches are comparatively easy to develop; as their developments are more based on the limited historical information about energy use pattern and macro-socioeconomic variables. However, these models are not able to provide an explicit representation of the final end-users in details and give a coarse analysis of energy use in the urban area. Bottom-up techniques can provide a connection between end-users on individual level with macro-socioeconomic indicators on urban level. As these models are based on the details on individual level, it is possible to consider micro variables related to the physical and behavioral characteristics of buildings and households, along with macroeconomic variables in different scenarios. However, these analyses require an extensive database of empirical data on energy use which the quantity and quality of these data could threaten the validity of these approaches. Acquisition and extraction of the physical and constructional data of buildings from the digital maps and aerial images has established a great chance to fulfill the large data requirements of urban bottom-up models without the need of visual inspection and long survey of the properties. This approach provides a quick and robust method, without costly on-site measurements, but still needed sophisticated 3D models and advanced techniques to extract appropriate spatial and geometrical variables.

5.2 Integrated Models

This review shows that each of the existing integrated models only addresses some specific parts of the whole urban energy system. Despite the diversity of approaches that are highlighted by the review, a number of common challenges such as sophisticated spatial variables, problem specific and data intensive, availability and credibility of data, policy relevancy and integrated multi-layer models can be identified.

5.2.1 Towards Integrated Multilayer Models

One of the major challenges involved in the development of integrated models is capturing the interaction and dynamics between different spatial scales and developing appropriate models that can capture these dynamics in macro and micro levels. It was observed that current integrated models are strictly constrained to one spatial scale such as building, neighborhood, district or city. In reality, energy consumption depends on different variables at different spatial scales. By constraining the simulation to one of these scales, all other variables that have effects at other scales, are faded out. Nowadays, for modeling at both macro and micro levels, reference models are available. On macro level, Top-down approaches such as Econometric or Statistical models have provided aggregate results. On micro level, Building Energy Performance Simulation Tools such as ESP-r,

ECOTECT and DOE-2 more deal with single buildings and do not address the upper spatial levels. Therefore, an integrated approach that allows examining the interaction of these levels is still missing.

There are two promising approaches for modeling this complexity; on the macro level, aggregate dynamics models and on the micro level, microsimulation and agent-based models. Aggregate dynamics models such as System Dynamics help us to understand the behavior of urban systems over time with use of internal feedback loops, time delays and stocks and flows, demonstrate how even seemingly simple systems display complexity and nonlinearity. Agent Based Models are computational methods that enable researchers to create, analyses and experiment with models composed of agents that interact within an environment. Agents perceive their environment and other agents; make decisions following some rules, and act, possibly changing the environment in the process. Most of the complex phenomena that happen in cities due to the interactions between agents and also environment can be addressed by this approach. In urban area, the interactions of agents at the micro scales and emergent patterns from them on the macro scale (bottom-up), and interactions from the upper scales into the agents (top-down) can be simulated with these approaches. While these approaches integrate with the energy models, it is possible to simulate energy flow in urban areas at different spatial levels.

5.2.2 Spatial Implications of Renewable Energy Technologies

The close interrelation between energy and space becomes obvious by looking at the historical development of cities, where almost 85 % of the worldwide energy is consumed. Today, these interactions have accelerated with the growing trend in the adoption of renewable energy technologies in supply side. Unlike the fossil fuels that are more based on the underground sources and have no significant spatial effects, renewable energy technologies have spatial and functional implications. Urban energy transition requires implementation of huge volume of these technologies in the urban area and consequently affects the spatial and functional structure of cities. Current models address the energetic effect of these technologies. However, this is just part of the analysis and it is of equal interest to consider the spatial aspects of these technologies as well. Recently, much progress has been made in urban spatial modeling. Spatial transition models concentrate on predicting how a city evolves over time under different policies and are commonly found in the area of land use/land cover and urban growth modeling such as OPUS/UrbanSIM, CommunityViz and TRANUS. Through these approaches, the urban system is considered as a complex system which is focused on space and time. Such models can establish robust platforms to incorporate energy models to demonstrate spatial implications.

5.2.3 Simulation and Optimization Methods

Simulation on urban scale involved with various aspects such as spatial, social, economic, technological and environmental issues over time. Therefore, simulating any issues, even at a small scale requires considering large number of variables. Analyzing of these variables and the possibility of identifying an optimal configuration to them based on the conventional computational methods such as statistical, mathematical or manual trial and error are not too realistic. As shown in Tables 1, 2 and 3, different simulation and optimization analysis methods already have been applied. Simulation methods such as System Dynamics, Statistical methods on macro level and Agent Based Models (ABM) or Microsimulation methods on micro level are the main candidates. Optimization methods such as Econometric approaches and Multi Objective Optimization Models including linear or nonlinear programming and genetic algorithms are also applied.

6 Conclusions

In this review, three main approaches that are used to simulate energy flow in urban area have been examined. The goal is to provide an up to date overview of them. The evaluation has been done based on the energy flow direction and the application focus of these models in the urban energy system. Accordingly, three main distinct categories of models were identified, including: supply, demand and integrated models. Each of these categories uses different assumptions and simulation techniques and relies on different levels of data. A critical review of these models is provided. Finally, some of the main issues that are missing in these models are highlighted, which open up new lines of research for researchers. These issues should be considered and integrated in developing new urban energy models in built environment to help designers and planners in simulating and optimizing their urban energy proposals in a more comprehensive way. These new challenges are:

- Integrated multilayer models.
- Spatial implications of renewable energy technologies.
- Integrated simulation and optimization methods.

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